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Abstract

Lateral variation in crustal attenuation of California is calculated by inverting 25,330 synthetic Wood-Anderson amplitudes from the California Integrated Seismic Network (CISN) for site, source, and path effects. Two-dimensional attenuation (q or 1/*Q*) is derived from the path term, which is calculated via an iterative least-squares inversion that also solves for perturbations to the site and source terms. Source terms agree well with initial CISN M_Ls and site terms agree well with a prior regression analysis. q ranges from low attenuation at 0.001 (*Q* = 1000) to high attenuation at 0.015 (*Q* = 66) with an average of 0.07 (*Q* = 143). The average q is consistent with an amplitude decay function ($\log A_0$) for California when q is combined with a simple geometrical spreading rate. Attenuation in California is consistent with the tectonic structure of California, with low attenuation in the Sierra batholith and high attenuation at The Geysers, at Long Valley, and in the Salton Trough possibly due to geothermal effects. Also, path terms are an order of magnitude smaller than site and source terms, suggesting that they are not as important in correcting for M_L.

Online material: Test of isotropic radiation assumption and L-curve analysis.

Introduction

An understanding of regional attenuation can help when interpreting of tectonic features, especially their thermal structure and water content. These features have a greater influence on attenuation than velocity, which is more commonly measured. The calculation of laterally varying (two-dimensional, 2D) attenuation can also help to constrain earthquake parameters that depend on amplitude like event magnitude. Previous studies of attenuation in California have been made for one-dimensional (e.g., Erickson et al. (2004); Ford et al. (2008)) and 2D (e.g., Mayeda et al. (2005); Phillips and Stead (2008)) cases.

In this study we make use of recent work to recalibrate the CISN local magnitude (M_L) scale (Hellweg et al., 2007). The project required the calculation of Wood-Anderson amplitudes measured at stations of the CISN for a good distribution of earthquakes, which resulted in over 30,000 amplitude measurements. Inspired by the work of Pei et al. (2006), we perform an M_L tomographic study of California and invert the amplitudes for source, site and path effects. M_L tomography provides a unique data set and perspective for examining the crust and attenuation in the frequency band that affects ordinary structures. We discuss the resultant terms and assess their significance in relation to California tectonics and the measurement of M_L.

Data and Method

The M_L recalibration study for the CISN (Hellweg et al. (2007)) used events with catalog $M_L \geq 3.0$ that occurred between 2000 and 2006, and in order to get an even distribution, the largest event in a 50 km grid was selected. In an attempt to obtain more recent measurements, a

second pass along this grid was made for events that occurred in 2006. This resulted in more than 200 events. Data at distances between 1 and 500 km from these events measured on the horizontal components was obtained from over 300 strong-motion and broadband stations of the northern and southern California networks, as well as some data from temporary deployments of the USArray. The Wood-Anderson seismograph response of these data were calculated (Uhrhammer et al. 1996) and the maximum amplitude on the trace was measured.

For this study, in order to obtain a more even magnitude distribution, data for events with M>5.5 were discarded. All events were recorded at more than one station. Also, if a station recorded an event with more than one instrument (strong-motion and broadband) the components were averaged so that each station had exactly two horizontal measurements. These criteria resulted in 185 events recorded at 335 stations (670 components) for 25330 amplitude measurements, which produced a very dense sampling of California (Figure 1a).

We employ the tomography method of Phillips and Stead (2008) where the Wood-Anderson amplitude A_{WA} at a given distance r and frequency f can be estimated by

$$A_{WA}(f,r) = S(f)R(\theta)P(f)G(r)\exp\left(\frac{-r\pi f}{QU}\right), \quad (1)$$

where $S(f)$ is the source spectrum and $R(\theta)$ is the source radiation in the source-receiver direction θ. $P(f)$ is the site term, and $G(r)$ is the geometrical spreading term. The final term is an apparent attenuation (parameterized by Q), where U is the group velocity of the phase that produces the amplitude measurement. In California, at short distances (~< 80 km) this phase is the direct

arrival and at greater distance (~> 120 km) it is a mix of crustal and Moho/surface reflections resulting in *Lg*. Between these distances (80-120 km) *Sn* and *SmS* are strong parts of the amplitude measurement. Despite the changing contributions to the measured amplitude, we make the simplifying assumption of constant U equal to 3.5 km/s. This group velocity is most appropriate for the phases recorded at greater distances, so some error will propagate into measured Q, though this is assumed to be small.

The log transform of eq (1) is

$$\log[A_{WA}(f,r)] = \log[S(f)] + \log[R(\theta)] + \log[P(f)] + \log[G(r)] - \frac{r\pi f}{QU} \tag{2}$$

We adopt a geometrical spreading term from Street et al. (1975) of the following form

$$G(r) = \begin{cases} \dfrac{1}{r} & r < r_0 \\ \dfrac{1}{r_0}\left(\dfrac{r_0}{r}\right)^{0.5} & r \geq r_0 \end{cases}. \tag{3}$$

The distance r_0 as well as a starting 1D Q model for California were found by fitting the amplitude decay function ($\log A_0$) used in southern California for determining local magnitude (Kanamori et al., 1999),

$$\log A_0(r) = 1.11 \cdot \log(r) + (0.00189r) + 0.591, \tag{4}$$

87 which is very similar to the CISN $\log A_0$ calculated by Hellweg et al. (2007), which will be used
88 for all of California. The best fit was given by r_0=200 and Q=150 (Figure 2), so that the
89 spreading for the maximum amplitude transitions from body-wave (r^{-1}) to surface-wave ($\sqrt{r}$) at
90 approximately 200 km. We validate the assumption of an approximately isotropic radiation
91 pattern (Figure S1 in the electronic supplement to this article) so that $R(\theta)$ can be approximated
92 by a constant and the amplitudes can be corrected using eq (3) and an initial Q model, then eq (2)
93 can take the form
94

$$\log[A_{WA}(f_{WA})] = \log[S(f_{WA})] + \log[P(f_{WA})] - \frac{\pi f_{WA}}{U}\int_s Q^{-1} ds \qquad (5)$$

95
96 where f_{WA} is the frequency band of the synthetic Wood-Anderson amplitudes, which can be
97 approximated as a two-pole highpass Butterworth filter with a corner at 1.25 Hz (Uhrhammer
98 and Collins, 1990), and is assumed to be approximately 1 Hz in this analysis. The form is put
99 into a damped first-difference least-squares inversion (LSQR, Paige & Saunders, 1982) to
100 calculate the source, site, and path terms in the Wood-Anderson band along the incremental ray
101 length, s. We chose a damping coefficient of 150 and a grid-spacing of 0.2^o based on an L-curve
102 analysis, where these 2 choices minimized the model length and residual variance satisfactorily
103 (Figure S2 in the electronic supplement to this article).
104
105 **Results and Discussion**
106
107 The event terms agree well with catalog magnitudes (Figure 3). The difference between the event
108 terms and catalog magnitudes (event bias) are centered on zero with a standard deviation of 0.25.

Site terms agree very well with station corrections, or station-network-component-location (SNCL) dM_Ls (Figure 4). These SNCL dM_Ls are obtained from a separate L-1 norm inversion (Hellweg et al., 2007), which required historical corrections to be maintained in the current algorithm. The constraint is evident in the SNCL dM_L histogram, which is shifted off a mean of zero. There are several outliers in this comparison. Two positive term outliers are the Transportable Array (TA) stations, P05C and R05C on the north and east components, respectively. This may be due to the small number of observations made during this temporary installation (ten and five, respectively). The negative term outliers (gray ellipse, Figure 5) each have more than sixty observations, but they are all located near the Long Valley region (Region B, Figure 1b). If the SNCL dM_Ls are correct, then the path term in this region is under-predicted, which would result in a greater q (higher attenuation) in this area.

Resolution of the path term is calculated via direct solution of the normal equations using Cholesky decomposition and the resolution length is estimated by taking the square root of the ratio of grid area to diagonal resolution element (Phillips and Stead, 2008). This length is contoured in Figure 1b and is highest in southern California at 0.5^o, where the network of stations is dense, but a resolution of 1^o is found for most of California.

Q is derived from the path term and ranges from 66 to a little more than 1000 in California. Its inverse, q, is directly related to attenuation and correlates well with geological and topographical regions (Figure 1b). Attenuation is high in the geothermal regions of The Geysers, Long Valley, and the Salton Trough (A, B, and D, respectively, Figure 1a) and low in the Sierra Nevada batholith (C, Figure 1a). As discussed earlier, we may expect q in the Long Valley region to be

even greater. There is a slight suggestion that high q may be associated with regions where faulting is observed. This is most evident along the Garlock Fault (latitude=35^{o}) and possibly the Hayward Fault system (latitude=37.5^{o}, longitude=-121.8^{o}). One of the most unexpected features of the tomogram is the relatively low q region in the San Francisco Bay Area, and several validation tests prove it to be a robust feature. Though absolute Q in this region (Q~200) agrees with Mayeda et al. (2005) and the 1-D model for the Bay Area of Malagnini et al. (2007), it differs from previous work by Ford et al., (2008) (Q~100). The reason for the discrepancy may be associated with the tectonics of the region. Ford et al. (2008) were careful only to measure attenuation in the Franciscan block (west of the San Andreas Fault), however this study uses paths that traverse both the Franciscan and Salinian blocks (east of the San Andreas Fault). In fact, Phillips et al. (1988) found a distinct difference in coda Q for the two regions, and though the absolute values are different between this study and their results, the ratios of the regions are similar. Furthermore, there is a suggestion in the results of Phillips and Stead (2008) that attenuation in this region may be lower relative to its surroundings.

The path term could act as a third correction for M_L in addition to the $\log A_0$ and SNCL dM_L corrections that are already applied when calculating M_L in California. However, the path correction is an order of magnitude smaller than the $\log A_0$ and SNCL dM_Ls (0.01 versus 0.1, respectively). Though, the effect of extreme Q structure in regions like the Sierra Nevada, The Geysers, and the Salton Trough may be large enough to warrant a path correction for paths affected by those regions.

Random error will not greatly affect the results presented here due to the excellent ray coverage and the damping used in the inversion. However, the assumptions employed here, namely isotropic radiation, and straight-line wave propagation that samples the crust will introduce systematic error into the interpretation. The isotropic radiation assumption may affect the data at short (<100 km) distances where the normalizing effects of scattering and dispersion do not play a large role, whereas the wave propagation assumption may affect the data at long (>300 km) distances where the measured amplitude may belong to a diving wave that has sampled the upper mantle. Finally, it is difficult to comment on intrinsic attenuation of crustal material in California because this method measures a path q that is a combination of both intrinsic and scattering attenuation.

Conclusion

We use of over 25,000 amplitude measurements made to recalibrate M_L in California to derive Q from the path term of an amplitude tomography method, which also solves for perturbations to the site and source terms. Source terms agree well with initial CISN M_Ls and site terms agree well with a prior regression analysis (Hellweg et al., 2007). Q ranges from 66 to 1000 with an average of 143. The average Q is consistent with an amplitude decay function ($\log A_0$) for California when combined with a simple geometrical spreading rate. Attenuation in California is consistent with the tectonic structure of California, with high Q in the Sierra batholith and low Q at The Geysers, Long Valley, and Salton Trough possibly due to geothermal effects. There is also increased attenuation along shear zones with active faulting. Our results in the San Francisco Bay Area agree with the 1-D analysis of Malagnini et al. (2007) and 2-D study of

177 Mayeda et al. (2005). A more complete *Q* model may aid in ground motion estimates for
178 California. Finally, path terms are an order of magnitude smaller than site and source terms,
179 suggesting that they are not as important in correcting for M_L.
180
181 **Data and Resources**
182
183 Amplitude data for California were obtained from the Northern California Earthquake Data
184 Center (NCEDC) and the Southern California Earthquake Data Center (SCEDC) as part of the
185 forthcoming California Integrated Seismic Network (CISN) earthquake magnitude reconciliation
186 project. Some plots were made using the Generic Mapping Tools version 4.2.2
187 (www.soest.hawaii.edu/gmt; Wessel and Smith, 1998).
188
189
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195
196 **Figures**
197
198 Figure 1. a) Inset, data coverage map of California, where grid nodes (0.2^o) are shaded according
199 to number of paths crossing them. Events (circles, N=185) and stations (crosses, N=335) used in

200 the analysis are also shown. b) Local magnitude tomography of California. The scale is given in
201 Q, and q (1/Q), where hot colors (red) are high attenuation and cool colors (blue) are low
202 attenuation. Regions discussed in text are annotated: A) Geysers, B) Long Valley, C) Sierra
203 Nevadas, D) Salton Trough.
204
205 Figure 2. Amplitude decay and attenuation functions. Dark solid line is the $\log A_0$ used in
206 southern California (Kanamori, 1999), which is very similar to one derived for all of California
207 (Hellweg et al, 2007). Dashed line is the geometrical spreading function given in eq (3). Light
208 solid line is a constant Q of 150 and dashed light line is the combination of the geometrical term
209 and the constant Q plus K=0.73.
210
211 Figure 3. Event term compared to catalog magnitude (CISN ML). Histograms along the axes
212 show the distributions of the event terms (top) and catalog magnitudes (right). The event terms
213 from the inversion agree well with the catalog magnitudes.
214
215 Figure 4. Station term compared to regression result for station-network-component-location
216 (SNCL) dML. Histograms along the axes show the distributions of the station terms (top) and the
217 SNCL dMLs (right). The station terms agree well with the regression result, but the mean is
218 shifted toward zero (as prescribed by the inversion). Two outliers (gray crosses) with a small
219 number of observations are annotated and another cluster of outliers is shown by the gray ellipse.
220
221 Figure S1. Corrected amplitude (crosses) variation with a) azimuth and b) distance for the 5 Feb
222 05 Alum Rock (M_W4.1) earthquake. The radial (dashed line) and tangential (solid line) radiation

pattern of the event is plotted in a) and the Kanamori et al. (1999) $\log A_0$ is plotted in b) (for which the amplitudes have been corrected). The gray region in b) is the mean magnitude (4.43) ± 2σ (σ=0.36), where the white line is the calculated M_W. The catalog M_L for this event is 4.42.

Figure S2. L-curve analysis, where the damping coefficient used in the inversion that produced the model and residuals is given for grid spacing of 0.2^o. The gray line is for a grid spacing of 0.1 ^{o}. A damping coefficient of 150 was selected (bold type) because it minimizes the root-mean-square (RMS) of the model and residual.

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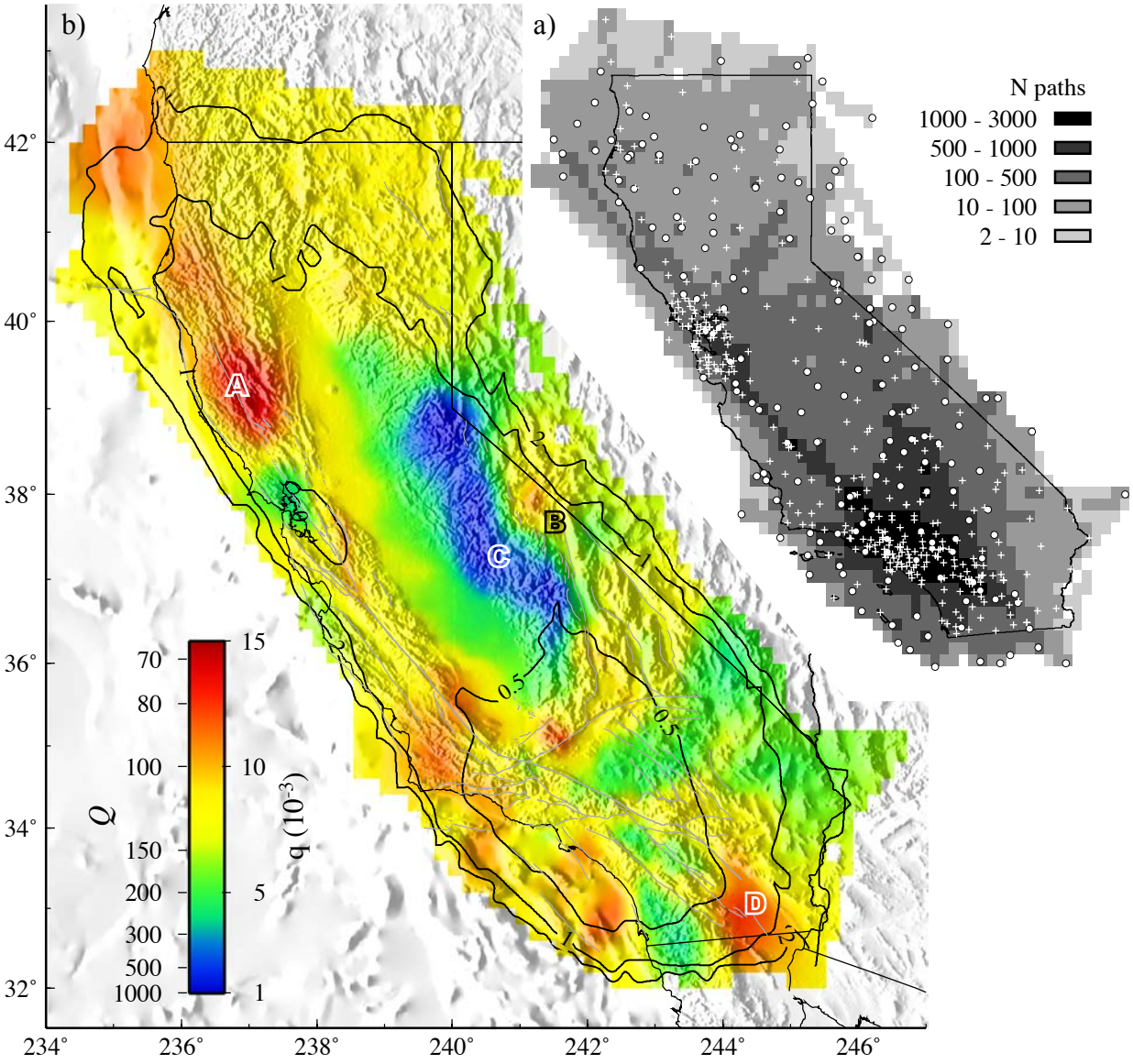
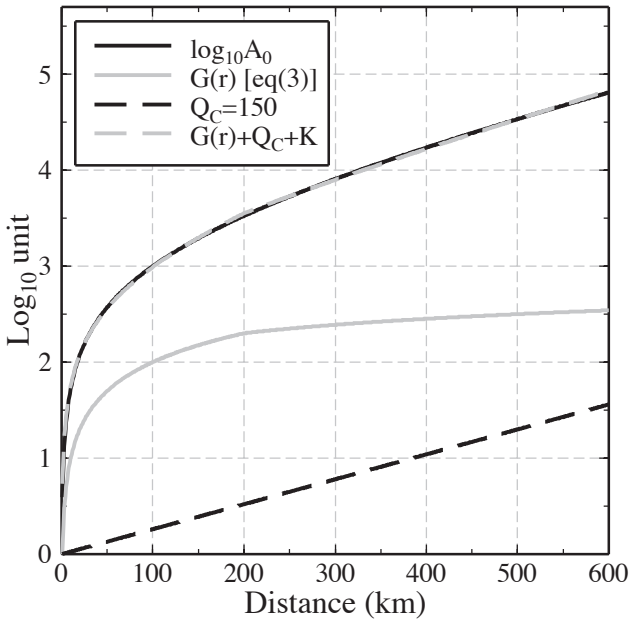


Figure 1.
Ford et al. (2009)
Version 1



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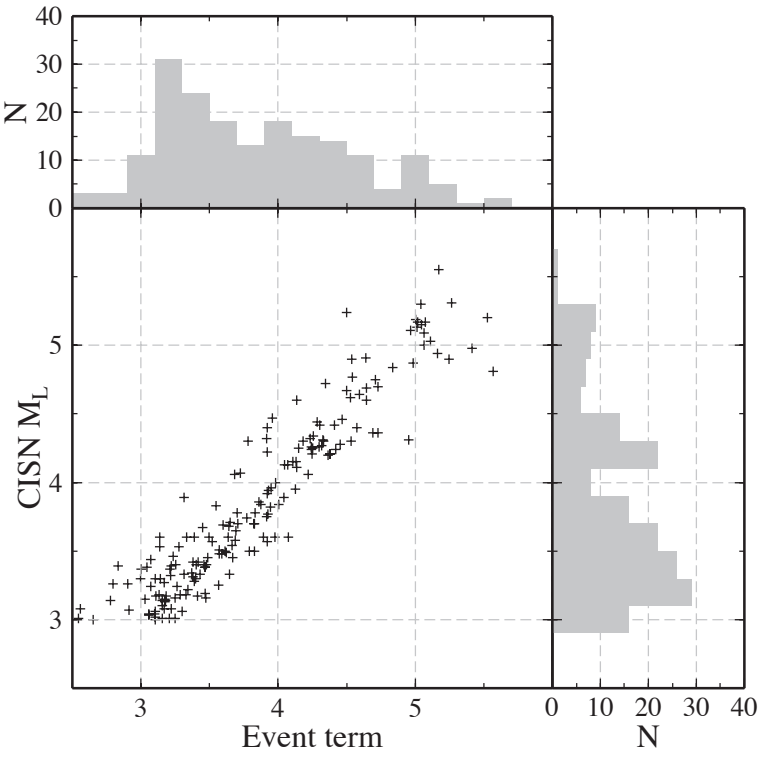

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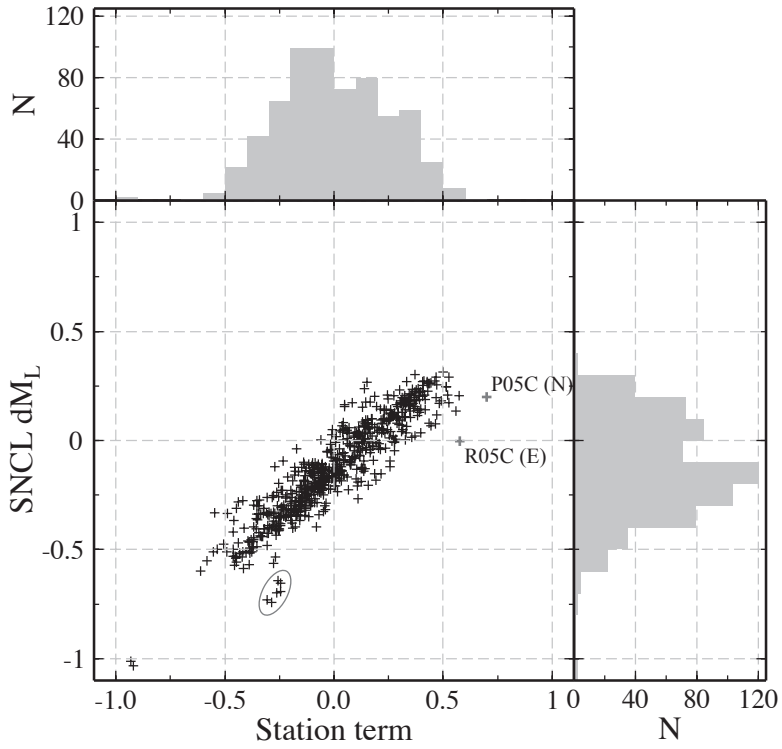

Figure 4.
Ford et al. (2009)
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